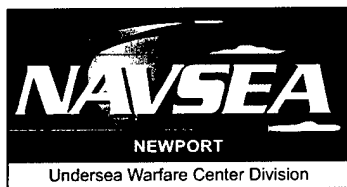


Rapid Environmental Assessment Methodology (REAM) of Coral Reef Ecosystems at the Atlantic Undersea Test and Evaluation Center (AUTEC) on Andros Island, Bahamas

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PREFACE

This work was sponsored by the Naval Air Systems Command in support of the environmental programs at the Atlantic Undersea Test and Evaluation Center (AUTEC).

The authors would like to acknowledge the assistance of Robert Pope and Lauren McCosh of the Naval Oceanographic Office in planning and acquiring the LIDAR data that were invaluable to the completion of this assessment. In addition, the authors would like to thank Philip Kramer for providing the *in situ* reef assessments data used in the verification analysis.

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Richard L. Bonin
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13. ABSTRACT (Maximum 200 words) The Atlantic Undersea Test and Evaluation Center (AUTEC) was established in the 1960s to meet the Navy's research, development, test and evaluation requirements. AUTEC is an undersea instrumented test facility located in the Tongue of the Ocean (TOTO) off the east coast of Andros Island in the Bahamas. The facility is adjacent to one of the largest near-shore coral reef ecosystems in the world. As part of the Navy's environmental stewardship, AUTEC has developed a baseline reef assessment methodology using high-resolution imagery data obtained from the IKONOS satellite and light detection and ranging (LIDAR) data. Analysis of these data allows for (1) the determination of the presence of reef structure in and around the waters adjacent to the AUTEC facility; (2) the classification of reefs into general groups, such as patch reef, reef crest, and fore reef; and (3) the assessment of the reef development in terms of long-term sustained growth. This report describes the methodology used in developing of the baseline coral reef assessment using remotely sensed data, results derived from the analysis of the data, and the verification of the methodology using <i>in situ</i> data collected by independent researchers.				
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**RAPID ENVIRONMENTAL ASSESSMENT METHODOLOGY (REAM) OF
CORAL REEF ECOSYSTEMS AT THE ATLANTIC UNDERSEA TEST
AND EVALUATION CENTER (AUTEC)
ON ANDROS ISLAND, BAHAMAS**

INTRODUCTION

The Department of Defense (DoD) has recognized the importance of preserving the coral ecosystems that are present in and around military training ranges and DoD facilities by the implementation of Executive Order 13089 (Coral Reef Protection). The DoD is committed to incorporating coral reef protection and conservation into military operational and training activities. This commitment is evident by the establishment and promulgation of the Coral Reef Protection Implementation Plan (reference 1).

In support of the environmental stewardship of the Atlantic Undersea Test and Evaluation Center (AUTEC), the Naval Oceanographic Office (NAVOCEANO) has been conducting near-shore environmental surveys for over 35 years and coral reef surveys on an annual basis for over 20 years. These coral reef studies have been conducted at AUTEC Site 1 and at remote down range sites using diver personnel to implement standard quadrat sampling methods and analysis (Spearman's rank correlation coefficient) to assess the changes in the biological communities associated with the coral reef ecosystem. The difficulties associated with this methodology include weather limitations, diver availability, site accessibility, and limited dive times depending on the depths of the surveyed reefs. The most significant drawback to this methodology is the limited area that is evaluated by the survey team as compared to the overall area of the reef. The area surveyed by the divers typically represents <0.008 of 1% of the reef.

The coral reef system associated with Andros Island is one of the largest coral reef ecosystems in the world. As such, this required the development of a methodology to assess the entire coral reef ecosystem vice basing the assessment on a fractional percent of the surveyed area. The methodology needed to address the following concerns: ability to assess entire coral ecosystems independent of site accessibility and weather; rapid assessment of reef ecosystems in terms of generalized characterizations of reef structure; reduction in the number of *in situ* measurements; and a reduction of the cost of coral reef assessment studies.

The methodology incorporates data collected from remote sensors that acquire data over vast areas in a cost-effective manner. The high-resolution IKONOS satellite imagery data provide a visual indication of the location of potential reef structure in both shallow- and intermediate-water depths using spectral band filtering of the multi-spectral image. Figure 1 shows a general view of Andros Island and the deep-water region off the east coast known as the Tongue of the Ocean (TOTO). The light detection and ranging (LIDAR) data provide verification of the reef structure, the depth of the bottom surface, and an estimate of the reef development in terms of long-term sustained growth by height density distribution.

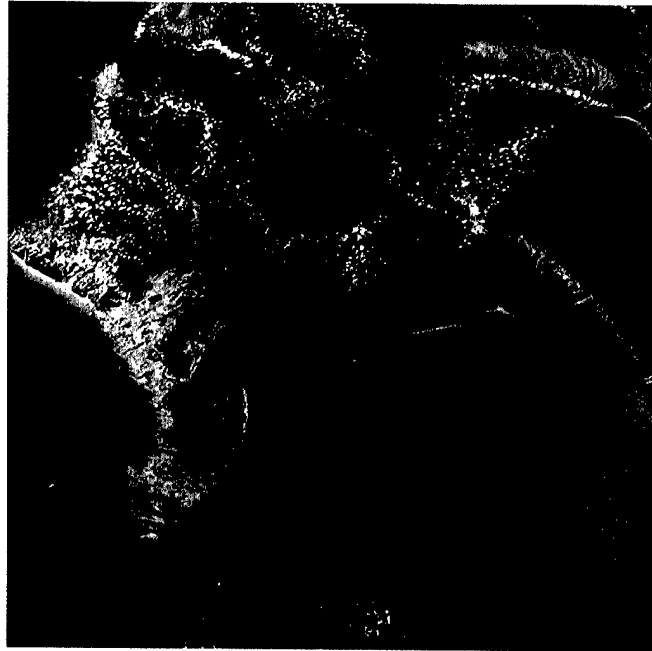


Figure 1. Satellite Image of the Tongue of the Ocean

STUDY AREA

AUTEC is located on Andros Island in the Bahamas approximately 177 nautical miles southeast of West Palm Beach, FL. Figure 2 depicts the location of AUTEC with respect to the Great Bahama Bank, the TOTO, and Andros Island. The TOTO is a deep-water canyon reaching depths of nearly 2100 meters and is surrounded by shallow waters on three sides. The shallow waters to the west of the canyon are the location of the Andros Island coral reef ecosystem, which stretches from the north end to the south end of Andros Island. The bottom topography and reef structure varies along the western edge of the canyon.

In the vicinity of AUTEC Site 1, the shore line progresses from land to a low-tide terrace that is composed of hardpan (limestone) and is covered in some areas by a thin layer of sand (reference 2). The terrace extends into a lagoon region that is characterized by an increase in

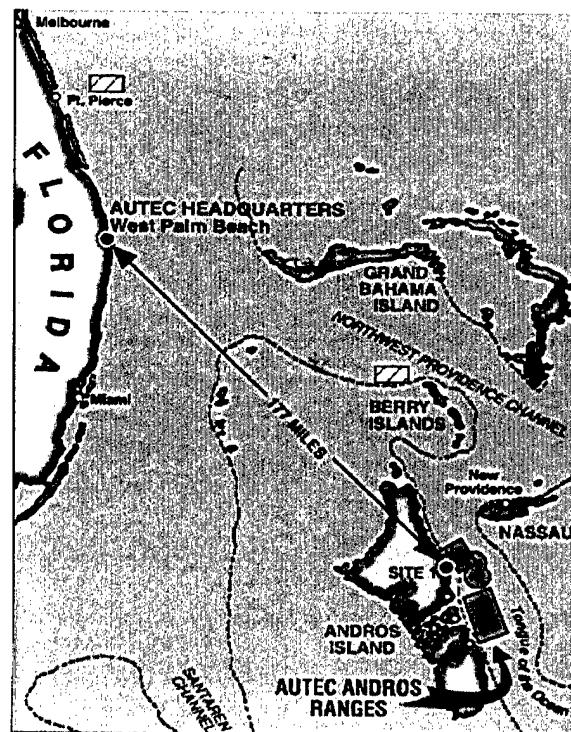


Figure 2. AUTEC, Andros Island, Bahamas

water depth up to several meters and is populated by small- to intermediate-sized, low-relief patch reefs and individual coral heads. The lagoon extends seaward and transitions to a barrier reef, or reef crest, that is typically characterized by near-surface or exposed coral formations. The reef crest is an area of high-wave energy that acts as a barrier for the lagoon system. The seaward platform, or rim, escarpment extends from the reef crest seaward and is characterized by a gradual increase in water depth to approximately 40 meters, at which point an abrupt dropoff occurs at the canyon rim. The rim escarpment is typically characterized as a fore reef. The AUTECH down-range sites (Site 2, Site 3, and Site 4) are located to the south of AUTECH Site 1 and are shown in figure 2. In the vicinity of AUTECH Sites 3 and 4, the bottom structure varies from that of Site 1, with an absence of a reef crest formation in many areas. In these areas, the low-tide terrace transitions to a lagoon area, which then transitions into a seaward platform prior to dropping off at the canyon rim.

The area located off AUTECH Site 1 was chosen for the study because of the high degree of variability in the reef structure, the availability of the IKONOS satellite imagery, the availability of LIDAR data, and the number of *in situ* measurement sites. The study area is bounded by the geodetic positions 24.695° north latitude, 24.715° north latitude, -77.7692° west longitude, and -77.73° west longitude.

DATA SOURCES

The IKONOS data for AUTECH Site 1 and the remote down-range sites were purchased from Space Imaging Corporation. Generally, IKONOS imagery can be obtained from the National Imagery and Mapping Agency (NIMA) archives for certain locations; however, no data were available for the areas of interest at AUTECH. The IKONOS data were provided in both a panchromatic (PAN) format and in a multispectral image (MSI) format. The PAN format is a monochromatic image with an XY spatial pixel resolution of 1 meter by 1 meter. The PAN data provide a relative spectral reflectivity response over the spectral band of 526 to 929 nanometers with a dynamic range of 2048 bytes (11 bits per pixel). The MSI format is a red-green-blue (RGB) image with an XY spatial pixel resolution of 4 meters by 4 meters. The MSI data provide a relative spectral reflectivity response that is comprised of three spectral components, the red band covers the spectral band from 632 to 698 nanometers; the green band covers the spectral band from 506 to 595 nanometers; and the blue band covers the spectral band from 445 to 516 nanometers. Within each band, the dynamic range is 2048 bytes. Both imagery datasets, i.e., PAN and MSI, were acquired on 25 April 2000 by the IKONOS-2 satellite sensor. The imagery was processed and referenced to the World Geodetic System 1984 (WGS84).

LIDAR is an emerging technology that uses a laser as an active remote sensing system, operated in either a profiling or scanning mode, to illuminate the land terrain and ocean bottom terrain. LIDAR data acquisition consisted of a laser scanning system on board an aircraft along with a kinematic Global Positioning System receiver to locate an XY position and an inertial

navigation system to compensate for the pitch and roll of the aircraft, thereby producing highly accurate geodetically referenced topographic and bathymetric data. The LIDAR dataset used in this analysis was acquired in November 2001 by the NAVOCEANO Airborne LIDAR Hydrography Group using a twin-otter aircraft (figure 3). The data were provided to AUTECH in two formats: an averaged dataset that corresponds to an XY spatial resolution of 8 meters by 8 meters and an unaveraged dataset that corresponds to



Figure 3. LIDAR Airborne Survey

an XY spatial resolution of 4 meters by 4 meters with a 25% overlap sampling. The precision of both the unaveraged and averaged data is 0.01 meters. Tidal gauges were installed at AUTECH during the LIDAR survey to correct the data for pressure and tidal variations. The bathymetric data that were generated from the LIDAR data are referenced to Mean Sea Level in order to correlate the data to existing NIMA referenced charts that were developed for AUTECH.

METHODOLOGY

The IKONOS dataset required preprocessing to geodetically align the data to known geodetic data that have been established on the AUTECH range. A center point analysis methodology was used to correct the IKONOS data for rotation alignment errors and correct for spatial variations within the image resulting from the off-axis alignment angle of the satellite. The second level of processing applied to the IKONOS data was to implement spectral-frequency filtering to enhance the visual location of reef structure beneath the surface. Stretching the red-frequency component of the image, i.e., the longer wavelengths from 632 to 698 nanometers, provides an enhanced visualization of reef structure in shallow water. Stretching the blue-green-frequency components of the image, i.e., the shorter wavelengths from 444 to 595 nanometers, provides an enhanced visualization of reef structure in intermediate water depths.

The LIDAR data provided by NAVOCEANO consisted of XYZ data points and required interpolation into a geodetically referenced gridded data set. Gridding is the process of using original data points (observed) in an XYZ dataset to generate calculated data points on a regularly spaced grid. Interpolation schemes estimate the value of the surface at locations where no original data exist, based on the known surrounding data values (observed). The Kriging method, chosen for the interpolation, is a geostatistical gridding method that produces visually appealing contour and surfaces. Kriging attempts to express trends that are suggested in the data, so that, for example, high points might be connected along a ridge, rather than appear as isolated bull's-eye-type contours. The unaveraged 4- by 4-meter resolution LIDAR data were used in this analysis to maximize the potential for the identification of reef structure relief. The spatial

resolution of the output grid was then increased to a 2- by 2-meter spatial resolution to take advantage of the 25% overlap in the sampling of the unaveraged data and to also take advantage of the Kriging gridding algorithm.

The geodetically corrected IKONOS data were then combined with the enhanced resolution grid LIDAR data to create a composite image of AUTECH Site 1 with bathymetric contours overlaid onto the satellite image. Figure 4 shows the composite image of AUTECH Site 1 and the adjacent waters. The bathymetric contour intervals correspond to a 1 meter depth difference and range from 0 meter at the shoreline to a water depth of 40 meters. The IKONOS imagery used in the composite image corresponds to a red frequency stretch, which highlights the shallow water reef structure.

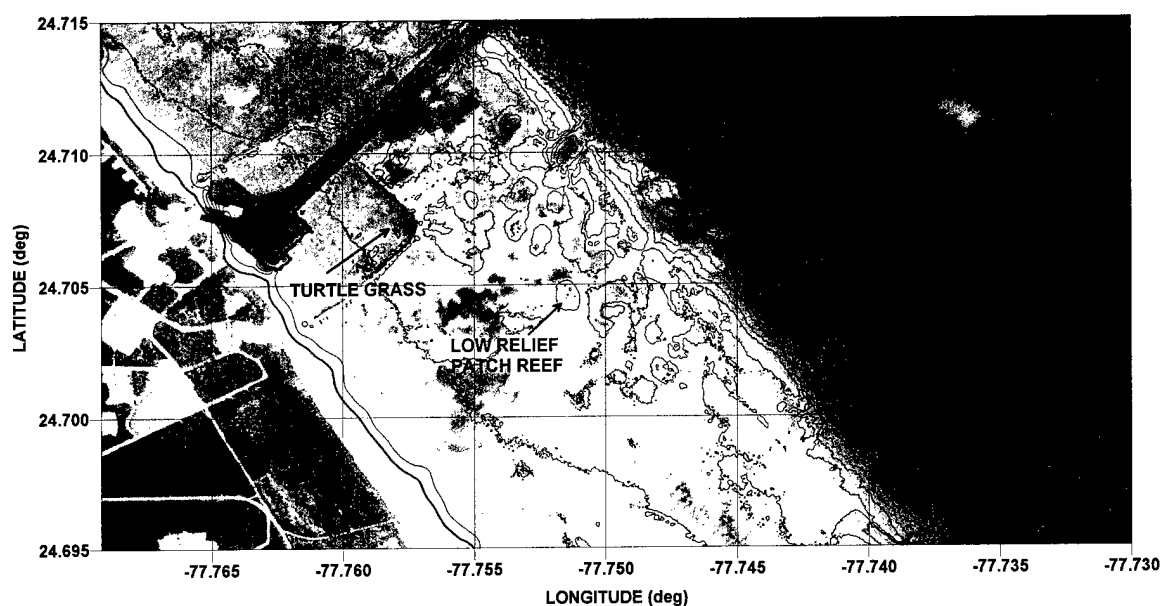


Figure 4. Composite Image of IKONOS Imagery and LIDAR Bathymetric Data

The grid LIDAR data were then used to generate a false monochromatic surface of AUTECH Site 1, specifically a shaded relief map, to further investigate the areas of interest. These maps use shading to indicate surface slope and slope direction relative to a user-defined light source direction. The light source can be thought of as the sun shining on a topographic surface. Figure 5 is a shaded relief image of AUTECH Site 1 that was combined with the enhanced resolution grid LIDAR data to create a composite image of AUTECH Site 1 with bathymetric contours overlaid onto the shaded relief surface.

The areas of interest in this study were further subdivided into two regions, i.e., Region 1 and Region 2. Region 1 is located directly offshore of the AUTECH Site 1 seawall and channel and is defined by the geodetic positions 24.710° north latitude, 24.715° north latitude, -77.756° west longitude, and -77.743° west longitude. Region 2 is located approximately one-half mile south of Region 1 and is defined by the geodetic positions 24.699° north latitude, 24.704° north latitude, -77.747° west longitude, and -77.735° west longitude. Regions 1 and 2 were chosen

for this analysis in order to compare the remote sensing data to *in situ* reef assessment data that were collected by independent researchers at four different locations within the two regions. The four comparison sites have distinct differences in the structural nature of the reef that allows for comparison over a broad range of bottom types.

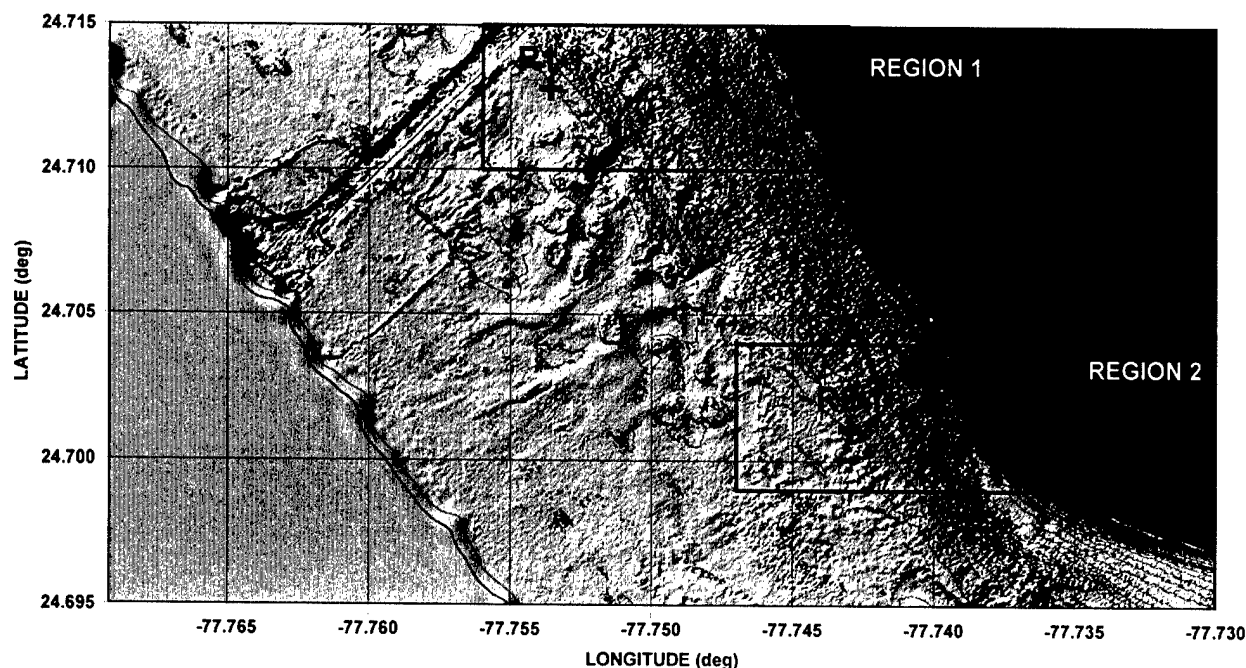


Figure 5. Composite Image of a LIDAR Shaded Relief Map and LIDAR Bathymetric Data

In situ reef assessment measurements have been conducted at AUTECH by NAVOCEANO, the University of Miami's Rosenstiel School of Marine and Atmospheric Science (RSMAS), and Perigee Environmental. Most recently, RSMAS and Perigee Environmental conducted reef assessment surveys off AUTECH Site 1 using the Atlantic and Gulf Rapid Reef Assessment (AGRRA) protocol. The AGRRA protocol is the first and only program that has developed an extensive regional database on Caribbean coral reef condition. Using an innovative regional approach to examine the condition of reef-building corals, algae and fishes, teams of reef scientists have assessed some 400 reef areas at 25 sites throughout the Caribbean region. The AGRRA protocol uses the following criteria to assess the coral reef ecosystem:

- Partial or total mortality of major reef-building corals by species and size;
- Relative abundance of principal algal types—macroalgae and crustose corallines; and
- Diversity of fishes and the abundance and sizes of key fish species.

For the purposes of this analysis, only the coral reef structure element information derived from the AGRRA data was used to validate the results derived from the remotely sensed IKONOS imagery data and the LIDAR bathymetric contour data. The specific sites that were used for comparison are R1-1, R1-2, R2-1, and R2-2.

RESULTS

The IKONOS data provided the identification of potential coral reef presence using the spectral frequency filtering imagery by enhancing the visual localization of reef structure beneath the surface. Stretching the red frequency component enhanced the visualization of reef structure in the shallow waters and the stretching of the blue green frequency components enhanced visualization of reef structure in the intermediate water depths. The composite image generated by the overlaying of the enhanced resolution LIDAR bathymetric data onto the IKONOS imagery (see figure 4) provided a method for visually discerning the presence of relief structure from non-relief structure. As an example, low-relief patch reef within the lagoon could be discerned from non-reef structure such as Turtle Grass (*Thalassia testudinum*) as shown in figure 4. The ability to differentiate between the relief structure and non-relief structure could not have been accomplished without the merging of the LIDAR and IKONOS data.

Detailed composite images of Regions 1 and 2 were generated using the LIDAR shaded relief maps and the LIDAR bathymetric contour data to further analyze the variations in relief height of the reef structure. Figure 6 shows the composite image of Region 1 and the locations of the *in situ* survey sites that were evaluated by independent researchers. It is evident from figure 6 that the shore line progresses from land to the low-tide terrace into a lagoon region that is characterized by an increase in water depth and is populated by small- to intermediate-sized, low-relief patch reefs and individual coral heads. The location of the reef crest, highlighted by the red contours, is evident by the long expanse of constant shallow-water depth. The survey site R1-1, located within the lagoon, just inside the reef crest, shows the absence of structural relief which is evident between the shoreline and reef crest. The mean height variation in and around survey site R1-1 corresponds to nearly zero. The survey site R1-2 is located on the seaward platform and corresponds to an area of low to intermediate relief. The height variation in and around the survey site R1-2 corresponds to a mean relief of less than 1 meter. This low- to intermediate-height variation extends over this section of the fore reef.

The composite image of Region 2 (figure 7) shows the locations of the *in situ* survey sites. Region 2 also shows the same transition as Region 1, from near shore to lagoon to crest reef and fore reef, with the reef crest contours highlighted in red. The survey site R2-1 is located on the reef crest. Although this area shows a low height variation, the location is indicative of *Acropora*, which tends to grow in dense formations with minimal interspacing between colonies. This type of reef structure is difficult to detect with a 2-meter grid resolution. The survey site R2-2 is located on the seaward platform and corresponds to an area of high relief height. The height variation in and around the survey site R2-2 ranges from 1 meter to 3 meters, with a mean height variation of 1.5 meters. This height variation extends over the upper section of Region 2. The lower section of Region 2 shows a decrease in the density distribution of high relief variations; however, some individual coral formations in this area have heights in excess of 5 meters.

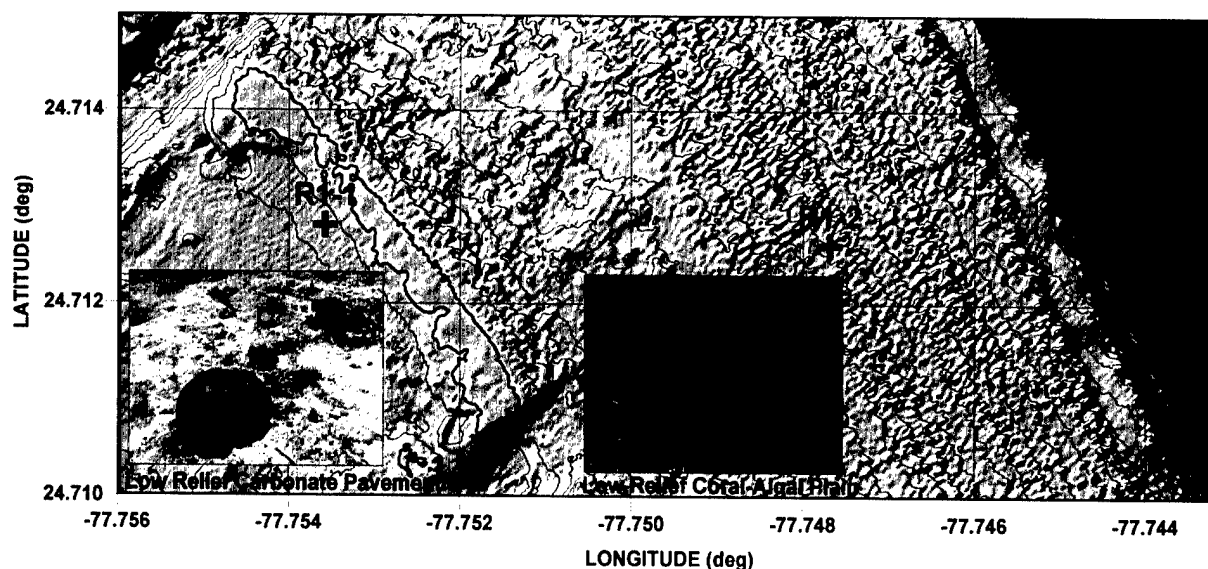


Figure 6. Composite Image of Region 1, LIDAR Shaded Relief Map and LIDAR Bathymetric Data

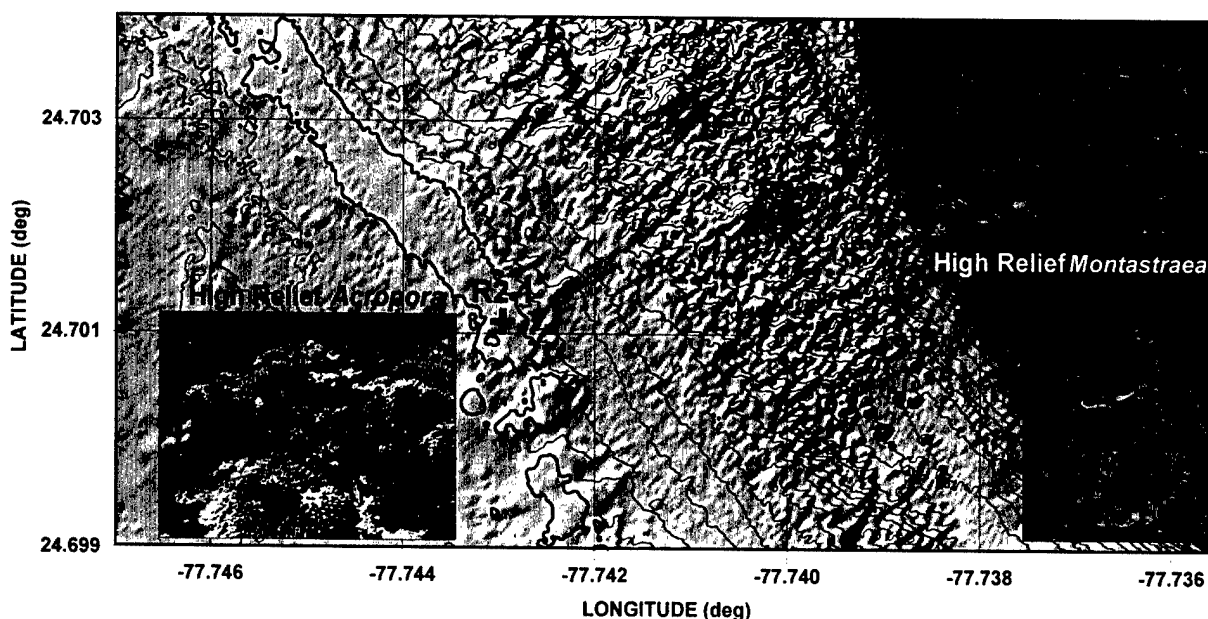


Figure 7. Composite Image of Region 2, LIDAR Shaded Relief Map and LIDAR Bathymetric Data

The data acquired by RSMAS and Perigee Environmental using the AGRRA protocol show excellent agreement with the results obtained from analysis of the IKONOS imagery data and the LIDAR bathymetric and imagery data. The AGRRA assessment of site R1-1 classifies this site as a reef crest consisting of a low relief carbonate pavement with a level of development classified as medium. The AGRRA assessment of site R1-2 classifies this site as a fore reef

consisting of a low relief coral-algal plain with a level of development classified as low. The low level of development is consistent with the interpretation of the remotely sensed data and corresponds to a reef system with a low level of sustained long-term growth. The AGRRA assessment of site R2-1 classifies this site as a reef crest consisting of a high relief *Acropora* coral formation with a level of development classified as high. The AGRRA assessment of site R2-2 classifies this site as a fore reef consisting of a high relief *Montastraea* coral formation with a level of development classified as high. This high level of development correlates extremely well with the high relief discerned from the LIDAR data and is consistent with a fore reef with a long-term sustained growth (reference 3).

SUMMARY AND FUTURE RESEARCH

The determination of reef structure, the classification of reef into general groups (such as, patch reef, reef crest, and fore reef), and the assessment of reef development in terms of long-term sustained growth using high-resolution satellite imagery IKONOS data and LIDAR data is an extremely promising methodology. As such, this methodology provides for the assessment of an entire coral reef ecosystem vice basing the assessment on a fractional percent of the surveyed area. The methodology addressed the following concerns: ability to assess entire coral ecosystems independent of site accessibility and weather, rapid assessment of reef ecosystems in terms of generalized characterization of reef structure, reduction in the number of *in situ* measurements, and a reduction of the cost of coral reef assessment studies.

Future research planned in this area includes the investigation of reef health (i.e., partial mortality and total mortality) using enhanced image processing methodologies. In addition, improved algorithms in the area of reef identification and the estimation of relief and density will be explored.

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